ELECTRON INJECTORS FOR NEXT GENERATION X-RAY SOURCES [*]

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DISCLAIMER

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ABSTRACT

Next generation x-ray sources require very high-brightness electron beams that are typically at or beyond the present state-of-the-art, and thus place stringent and demanding requirements upon the electron injector parameters. No one electron source concept is suitable for all the diverse applications envisaged, which have operating characteristics ranging from high-average-current, quasi-CW, to high-peak-current, single-pulse electron beams. Advanced Energy Systems, in collaboration with various partners, is developing several electron injector concepts for these x-ray source applications. The performance and design characteristics of five specific RF injectors, spanning "L" to "X"-band, normal-conducting to superconducting, and low repetition rate to CW, which are presently in various stages of design, construction or testing, is described. We also discuss the status and schedule of each with respect to testing.

Keywords: Electron Injectors, X-Ray Sources, Accelerator, Superconducting, Energy Recovery Linac (ERL), Free-Electron Laser (FEL)

1. INTRODUCTION

The success of many next generation x-ray sources and their applications is contingent upon the performance of the injector that is used to generate the electrons. They include energy recovery linac-based (ERL) sources[1,2,3] that are a major step beyond present third generation synchrotron light sources, self-amplified spontaneous emission (SASE) free-electron laser (FEL) sources such as the linac coherent light source (LCLS)[4] and the European XFEL[5] project of the TESLA[6] collaboration as new fourth generation light sources, and Compton backscatter sources (CBS)[7,8,9] for medical, protein crystallography and other applications. The underlying theme for the ultimate success of all these x-ray generators is the delivery of high-brightness electron beams to the radiation production region, whether it be an undulator or wiggler for the FEL-interaction-based sources, a bending magnet for synchrotron radiation-based sources or a laser beam for the backscatter sources. However, while beam quality is a critical factor for all of these devices, each requires a different set of beam parameters. Consequently, there are performance trade-offs that lead to quite different optimal electron beam injector configurations for the different applications.

ERL and SASE-based sources are particularly demanding with respect to electron beam performance. Typically an ERL light source injector is required to produce an electron beam with an energy of 5-15 MeV and an average current of 100 mA or more using CW RF acceleration. This type of electron beam, with an average power in the range of 1 MW, cannot be produced using the typical normal-conducting BNL/SLAC/UCLA-style RF gun[10] due to serious thermal issues associated with the high-duty factor. On the other hand, the beam requirements of a SASE device do allow the use of a more conventional RF gun design. For instance, the LCLS injector is specified to operate with a maximum

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gradient of 140 MV/m at a 120 Hz repetition rate and will generate a 4 kW average thermal load. We have performed an internal study of the modifications required to adapt a BNL/SLAC/UCLA-style gun to the LCLS-level thermal loads[11] which is not reported here. However, in this case, the normalized rms transverse emittance requirement of less than one micron at 1 nC per bunch is extremely challenging. In contrast, Compton backscatter x-ray machines can operate with more relaxed electron bunch requirements, typically 1 nC at a transverse rms emittance value of a few microns. However, higher charge and duty factor would greatly benefit some applications that seek high x-ray flux and improved electron beam quality would generate higher quality x-rays with respect to energy spread and divergence. Hence, as Compton backscatter systems evolve, we expect that the electron injector beam performance requirements will be pushed to higher levels and the thermally-modified conventional RF gun that meets LCLS specifications may be a suitable candidate as well as other guns we describe below.

The electron beam injector requirements for these advanced x-ray sources are summarized in Table 1. Of particular note are the short pulse length and the stringent requirements on the transverse emittance, at high bunch charge in all cases except the ERL. These parameters are compared below to the performance of five specific electron guns and injectors presently under development by Advanced Energy Systems (AES)[12] and collaborators.

Parameter	ERL[1]	SASE FEL[4]	CBS[7]	Units
Charge	~ 80	1000	> 1000	pC
Average Current	> 100			mA
Normalized Transverse Emittance	< 1.5	< 1	< 3	microns rms
Bunch length	3	10	10	psec rms
Longitudinal Emittance	40			keV-psec rms
Energy	7 - 10	~ 5	~ 3	MeV

Table 1. Typical electron beam injector requirements for advanced x-ray sources.

High-brightness, short-pulse beams are most easily produced by photocathode electron guns[13]. In conjunction with collaborators, we have been active in the development and application of advanced, high-brightness electron sources for various applications that include advanced x-ray sources. Five specific photocathode-based electron gun and injector projects are described in this paper and compared to the requirements of Table 1. These designs can find application in all three identified categories of x-ray sources that span the range from high-power, CW beams to ultra-high-brightness, high-peak but low-average-current beams. The first three injectors deliver high-brightness, high-power beams that are suitable for use in ERL-based light sources and also meet the requirements for high-power IR[14] and UV[3] FEL systems. These injectors as designed for similar applications and have equivalent output current, but utilize very different approaches to deliver the required performance. The first injector closely couples a DC gun to a superconducting accelerating structure consisting of single-cell cavities. The second, which is similar to the FZ-Rossendorf device[15], is a fully superconducting RF gun except for the cathode region. The third gun is CW and normal-conducting so that it is required to address the associated thermal load that is greater than 0.5 MW. The last two guns have more modest performance. One is a CW fully superconducting gun capable of average currents approaching 1 mA. Unlike the second device, this SRF gun utilizes the niobium itself as the photocathode emitter. Finally, we are developing an axisymmetric X-band RF gun to produce extremely bright, 1 nC-level electron pulses.

2. DC GUN AND SRF INJECTOR

A DC photocathode gun closely coupled to a superconducting RF (SRF) booster accelerator, as shown in Figure 1, is a promising high-power injector. The device begins with a Jefferson Lab designed 500 kV DC gun[16] followed by an emittance compensation solenoid[17]. This captures the electron beam and transports it to a 748.5 MHz SRF cryomodule consisting of three single cell cavities that accelerate the beam to 7 MeV. When every RF bucket is filled with 133 pC, this provides an average current of 100 mA and an average electron beam power of 700 kW. The sequence of single cell cavities provides latitude for adjusting the longitudinal phase space through different cavity phasing. The single cell cavity approach also permits scaling to bunch charges higher than 100 mA, and ameliorates high-order mode (HOM) and beam breakup (BBU) effects driven by high current. Higher current is not appropriate for ERL beam quality

requirements, but is of interest in other applications. The use of 748.5 MHz means that the injector is compatible with the existing Thomas Jefferson National Accelerator Facility (JLAB) ERL FEL ring and could subsequently be used to drive a 100 kW IR FEL upgrade of that device given the projected performance. At these power levels, there are several attractive FEL commercial material processing applications[18].
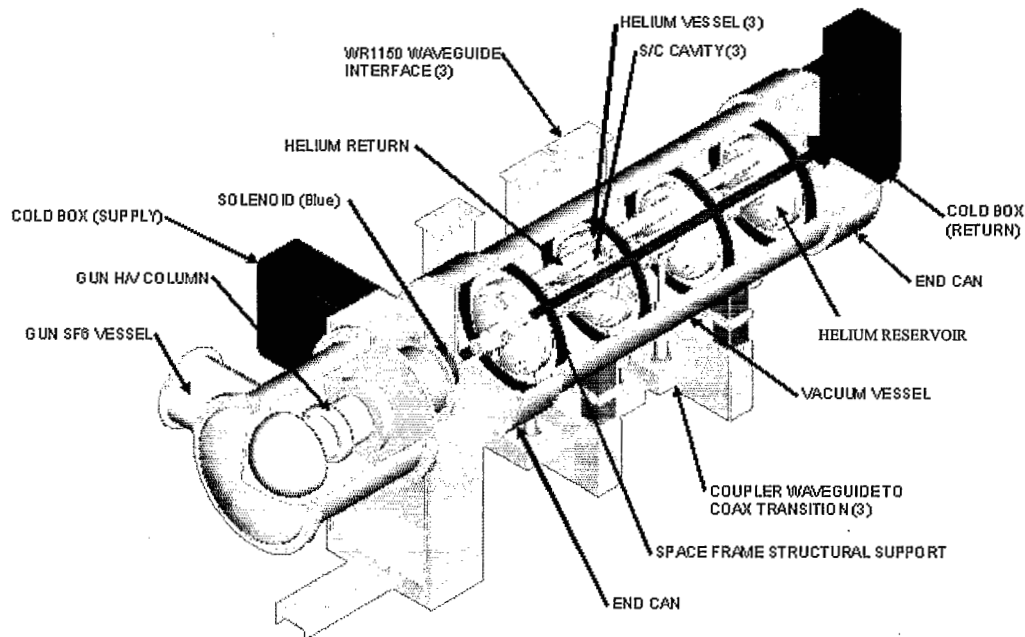

Figure 1. DC gun and SRF booster high-power CW injector.

As the bunch charge is increased beyond 150 pC, space-charge aberrations begin to degrade the beam quality. We have shown that the addition of a longitudinal phase space correction cavity that operates at a harmonic of the fundamental RF frequency can significantly improve the beam quality. Specifically at 1 nC, this configuration can deliver 5.1 microns transverse and 43 keV-psec longitudinal rms emittance[19]. Although, in principle, these charge levels are not required for proposed ERL light source performance, a harmonic cavity could be used to push ERL injectors to higher performance.
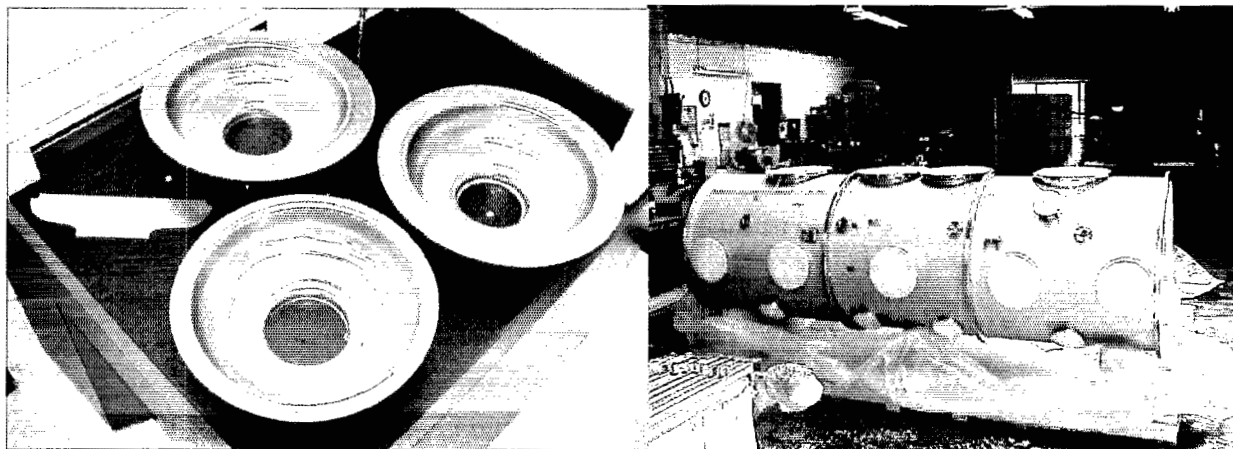

Figure 2. SRF half cells (left) and booster cryomodule vacuum vessel (right) for the DC gun and SRF injector.

Figure 2 shows SRF half cells prior to e-beam welding and the completed booster cryomodule vacuum vessel for this injector. Booster component fabrication will be completed in 2004 with cyromodule cleaning and assembly to follow at JLAB in 2005. The fundamental RF power couplers that will be installed initially are limited to 30 mA average current though a replacement coupler capable of delivering more than 500 kW, which will easily support 100 mA CW operation, is under development at AES[20]. Initial testing at JLAB is not anticipated before late 2006 due to the time required to install the RF power components and set up an injector test stand at JLAB. Those initial tests will use the full bunch charge and may even attempt to demonstrate up to 1 nC at low pulse repetition frequency (PRF), due to initial RF power limitations. Later RF power upgrades should enable 100 mA characterization in 2007.

3. CW NORMAL-CONDUCTING RF GUN

The second high-power injector approach is a normal-conducting, CW, photocathode RF electron gun that is shown in Figure 3. Los Alamos performed the physics and RF design of this 700.75 MHz, 2½-cell, 3 nC device that delivers 100 mA at a 35 MHz PRF. Note that the same gun would deliver 1 A at 350 MHz PRF with the identical thermal load. The crucial issue for this concept is the extremely high-average-power and the peak power densities that result from the resistive losses in the copper of the gun. Consequently, the initial engineering study focused on cooling strategies and the thermal analysis of the gun cells.
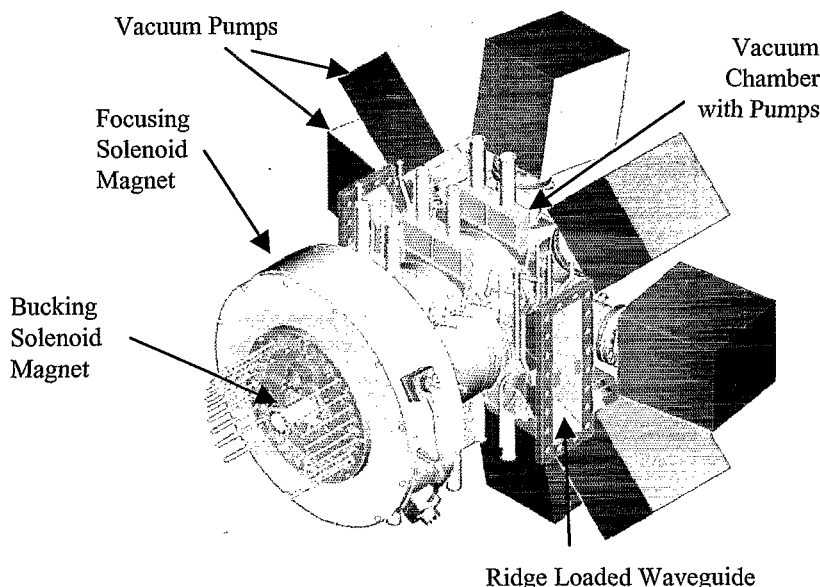

Figure 3. Normal-conducting CW 2½-cell RF gun.

Two dimensional and three dimensional thermal, stress, and displacement analyses were conducted on the gun design with the effects of temperature and pressure coupled with the RF response all taken into account. An example of these calculations is shown in Figure 4, which illustrates the radial displacements due to the calculated stresses. The 2-D analysis showed that for an input water flow rate of 36 liters/second at 20 C, the peak steady-state RF surface temperature reaches 52 C, the steady-state peak von Mises stress is 7,824 psi, and the transient peak von Mises stress is 14,308 psi. The coolant reaches a temperature of 26 C at the outlet, while the radial displacement on the cell walls is 0.0015 inches. The total thermal load of the gun is about 720 kW, but the analysis indicates the design coolant flow will adequately cool the device.

A low-power model, shown to the left in Figure 5, has been fabricated and tested, verifying the RF design of the gun cavities and input coupler. In addition, a test article, also shown in the center of Figure 5, was manufactured to confirm the cooling flow characteristics of the gun. In particular, the goals were to determine whether there are any areas of

starved flow, quantify the effects of blockage with thermal transients, and compare the results to the analytical model. It was found that the cooling channel design is satisfactory. The complexity of the thermal problem is illustrated by the machined cooling channels in the gun septum that are shown in the right of Figure 5.
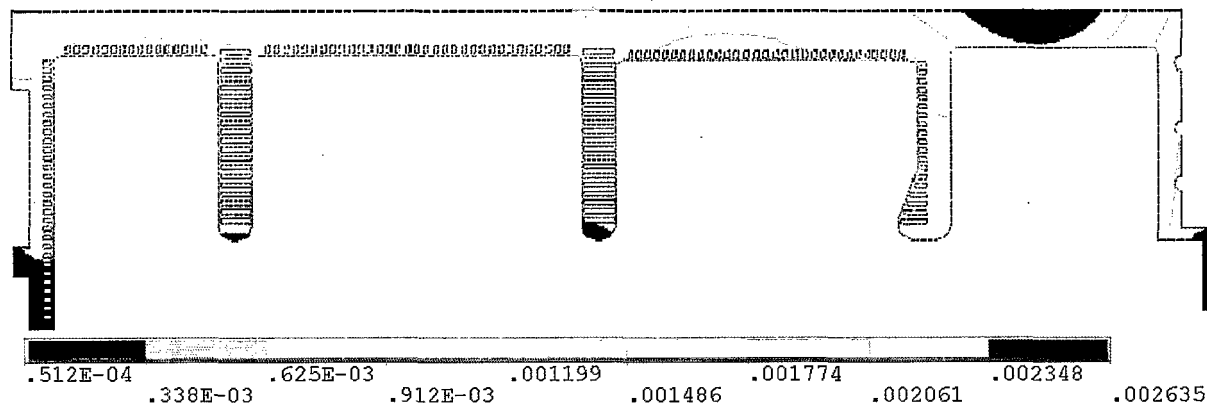

.512E-04   .625E-03   .001199   .001774   .002348
    .338E-03   .912E-03   .001486   .002061   .002635

Figure 4. Steady state radial displacements due to combined temperature and pressure forces.
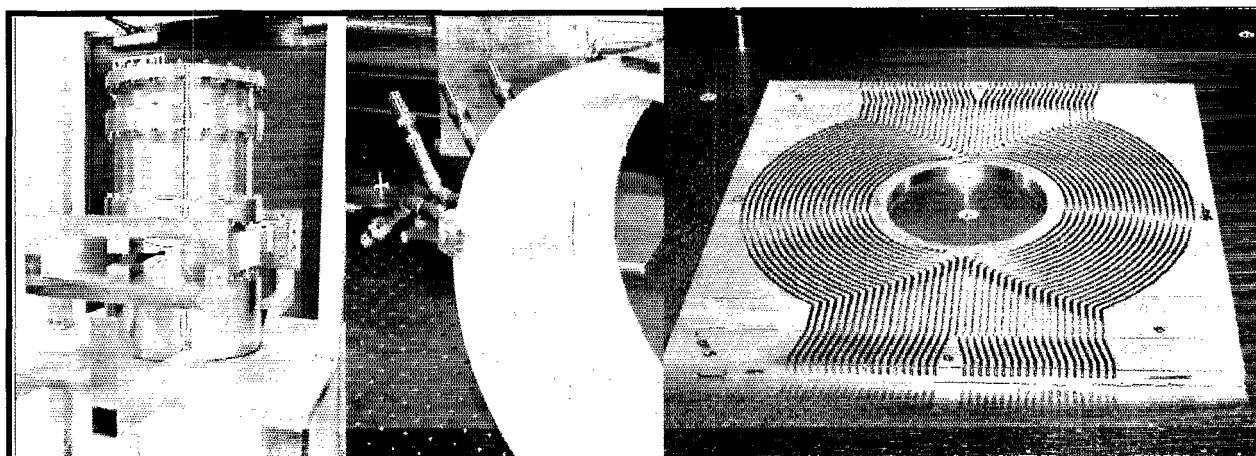

Figure 5. Low-Power model (left), cooling flow test article (center), and septum cooling channels (right)
of the normal-conducting CW gun.

This injector is presently in fabrication and scheduled for delivery to Los Alamos for testing in mid 2005. The existing Los Alamos 1 MW RF test stand will be used to perform a thermal test in late 2005. At this time there is insufficient installed RF power at Los Alamos to perform a beam test of the gun.

4. SUPERCONDUCTING RF GUN (WITH NORMAL CONDUCTING CATHODE)

The last high-power injector we describe is under development in collaboration with FZ-Rossendorf (FZR), Brookhaven National Laboratory (BNL), and JLAB. Because of our interest in very high-average-current, we have had to depart substantially from the present FZR 3½-cell design at 1.3 GHz[15]. Two fundamental design changes are the adoption of a ½-cell gun at the lower frequency of 703.75 MHz in order to accommodate the higher current of 200 mA or more required for ERL projects and the electron cooling rings for the Relativistic Heavy Ion Collider (RHIC)[21] at BNL. We have also increased the cathode stalk radius to 1.25 cm to permit active cathode cooling and higher bunch charge extraction. Our design assumes the gun will be followed by an SRF booster cavity as shown in Figure 6, which shows an FZR-style choke joint for the isolated and separately cooled cathode stalk which is not at superconducting

temperature. Beam dynamics calculations for this configuration show very promising performance. Primarily because of thermal issues, but also for simplicity of fabrication and reliability, we determined to utilize a quarter wave choke joint concept that is different from the FZR approach. In addition, a novel cathode concept is being studied for integration with the choke joint[22].

We have performed a thermal analysis of this SRF gun with both choke joints. At the current levels of interest, the photocathode drive laser and cathode heat loads become very significant and require active cooling. For 0.5 A operation, which is of interest to a BNL ERL proposal as noted below, with the quarter wave choke joint, we estimate a thermal load approaching 100 W in the cathode vicinity. With active liquid nitrogen cooling, Figure 7 shows that the cathode can be adequately cooled at this load level.
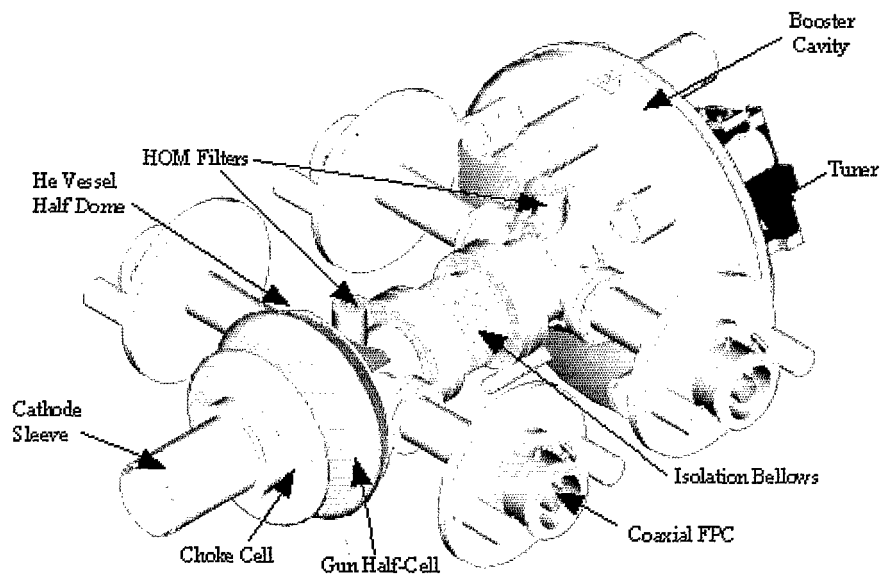

Figure 6. ½-cell fully superconducting gun followed by booster accelerating cavity.

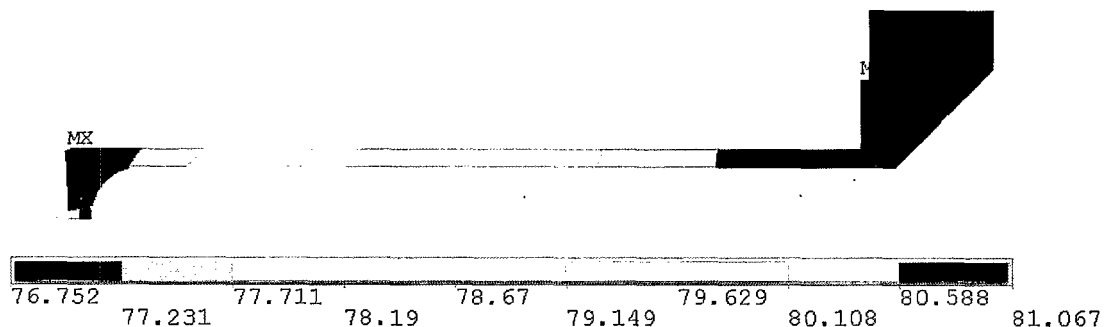| 76.752		77.711		78.67		79.629		80.588
	77.231		78.19		79.149		80.108		81.067

Figure 7. Thermal model of quarter wave choke stalk showing the temperature variation of less than 5 degrees from the cathode (left) to the main stem connection point (right).

For ERL light source, RHIC electron cooler and e-RHIC requirements, a design modification to produce a 1½-cell gun followed by a two cell SRF booster cavity would probably be advantageous and provide better beam dynamics performance. However, there is a desire to be able to produce a 0.5 A beam at 2 MeV from the gun with the 1 MW of

703.75 MHz of RF power installed at BNL in order to do a high current ERL test with the cryomodule described in the next section. As a compromise, the gun cryostat is being designed to also house a 1½-cell gun. The development of this injector is less mature than the previous two devices and the present schedule calls for a design review at the end of 2004. A decision as to whether to proceed to construction will be made in early 2005. The desired delivery date to BNL for testing is in 2006.

5. HIGH-CURRENT SRF CRYOMODULE

The x-ray source and other applications envisaged for the three high-power injectors described above will all require further acceleration, and in most cases, recirculation for energy recovery. This acceleration and energy recovery will utilize an SRF accelerating section in order to keep RF losses low. Figure 8 shows a copper cold model of a multi-cell accelerating structure designed at BNL that we are fabricating for use in high-current ERL devices. The design is projected to have a BBU threshold of at least 1.8 A, well in excess of the required ERL beam current of 100 mA.
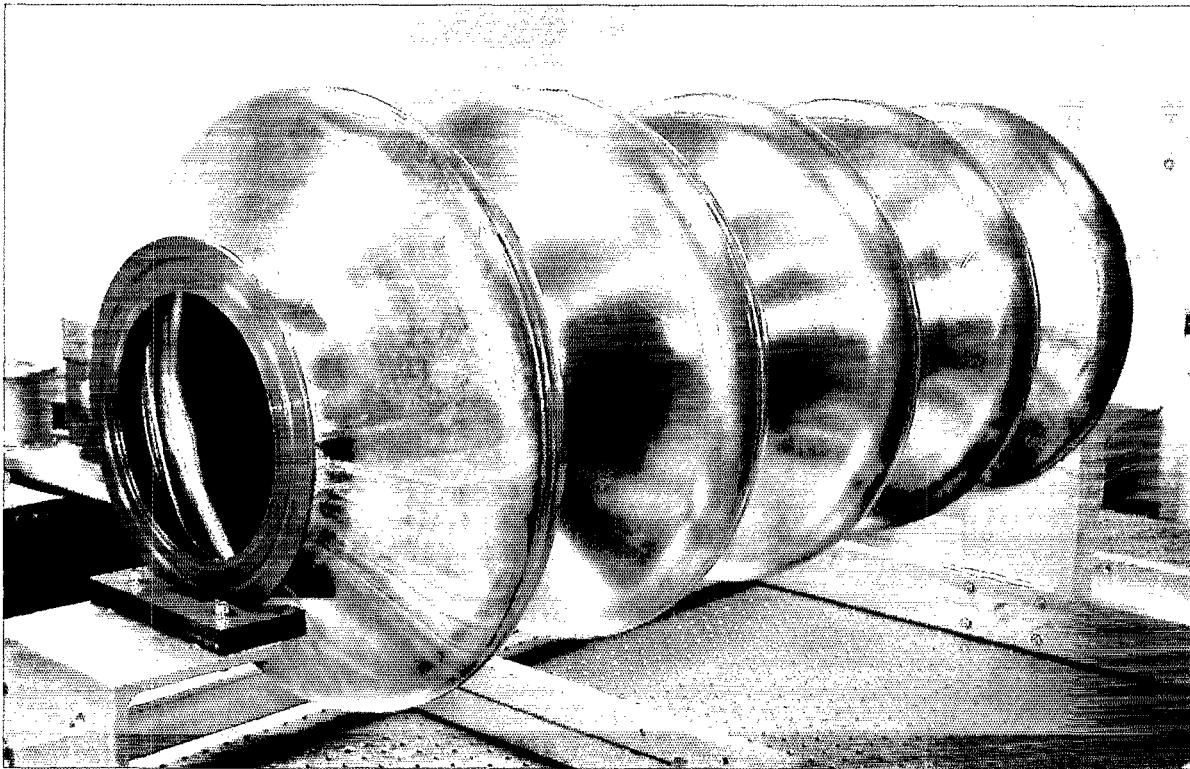

Figure 8. Low-power model of high-current 5-cell superconducting BNL RF accelerating structure.

BNL have proposed an ERL test using the Section 4 SRF gun and the section 5 SRF cavity as shown in Figure 9. This builds upon facilities and equipment already existing at BNL. The only elements which are not presently in procurement or fabrication are the injector and the fairly straightforward beam transport system. The gun can deliver a CW current of 0.5 A which is accelerated to 22 MeV and then recirculated through the 5-cell cryomodule before entering the beam dump. This setup would deliver an early energy recover demonstration with a total beam current of 1 A and lend credence to next generation ERL x-ray sources.
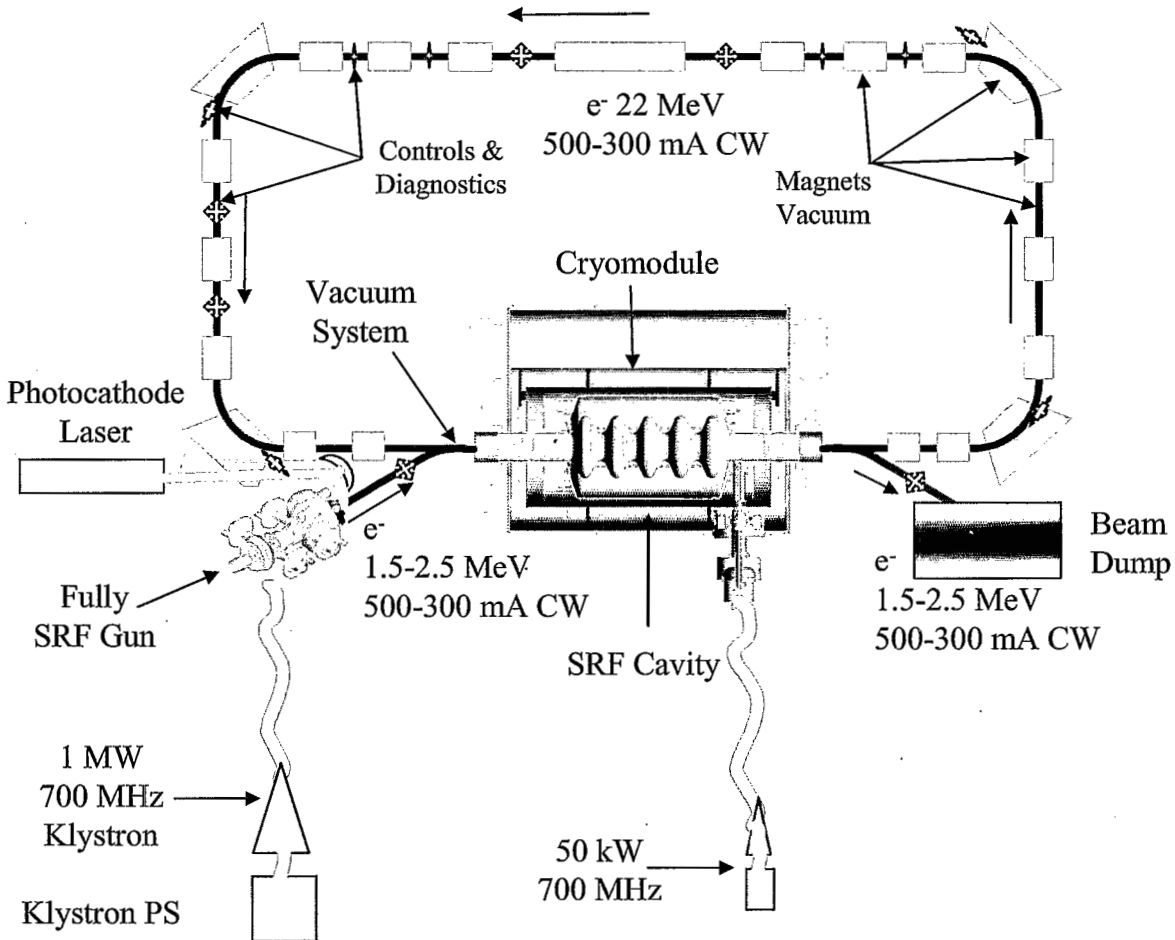
Figure 9. Schematic Diagram of proposed BNL high-current ERL experiment.

5. FULLY SUPERCONDUCTING RF GUN (WITH NIOBIUM CATHODE)

The final two injectors address high-performance rather than high-average-power. The first of these is a 1.3 GHz ½-cell gun, where the cathode area consists of the center portion of the backwall of the cavity. Two of these guns were fabricated and are shown in Figure 10. For simplicity and reliability, the cathode material is niobium, making the gun fully superconducting. The quantum efficiency of the niobium will be enhanced, through the Schottky effect, by the high electric field at the niobium emitting surface.

The Q-factor test results for these guns are shown in Figure 11. The cryomodule for beam testing is assembled and quantum efficiency testing is expected to begin at BNL in the summer of 2004. The test setup that will be utilized is shown in Figure 12. With an expected capability to deliver nearly 1 mA CW beams with transverse rms emittance below one micron, these guns are well suited to those applications that require very high-brightness CW beams.
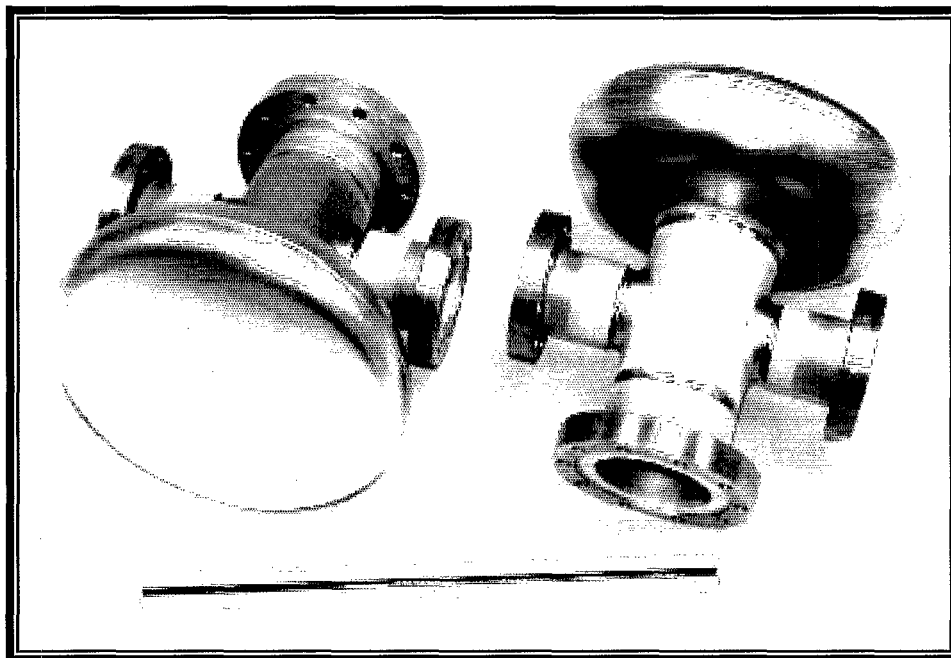
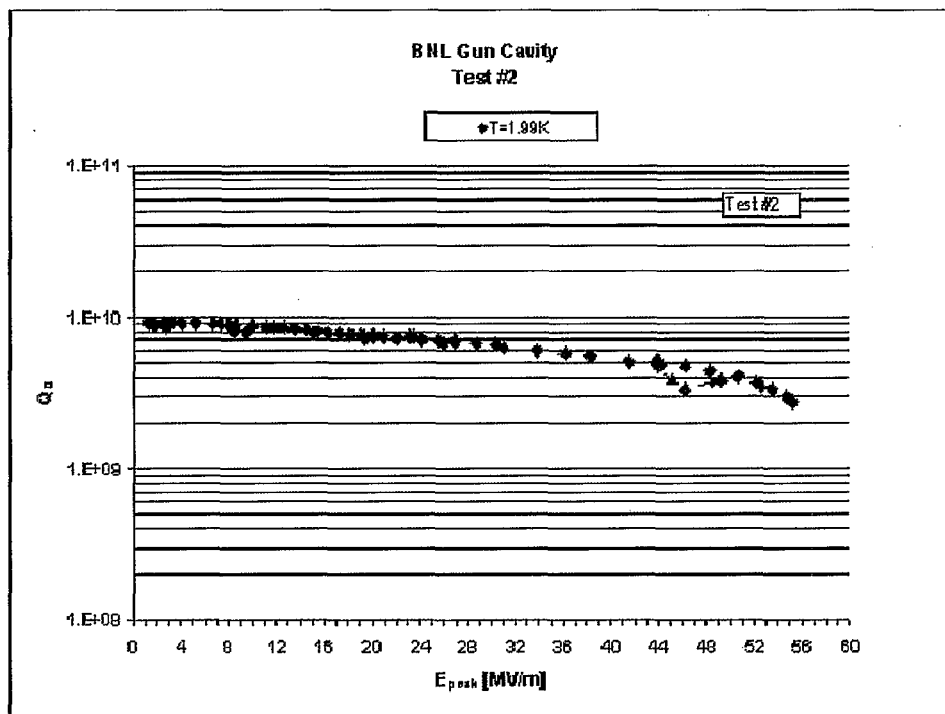Figure 10. Two ½-cell SRF guns with niobium cathodes.

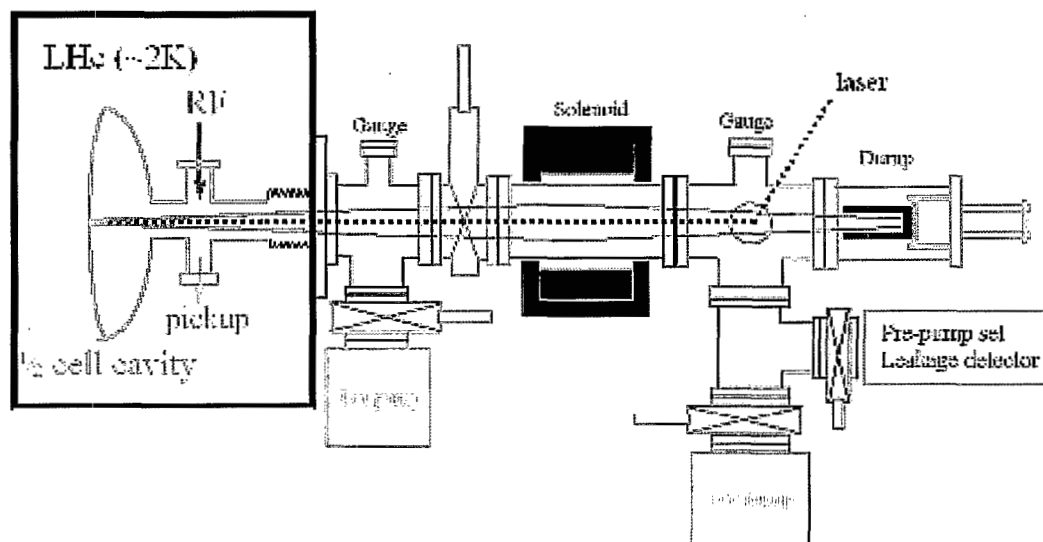Figure 11. Results of cavity field measurements after chemical polishing and high pressure rinse.

Figure 12. Test setup for quantum efficiency measurements of all niobium SRF gun.

6. AXISYMMETRIC GUN

The 1½-cell axisymmetric gun represents the next step in our development of higher performance injectors with reduced emittance. This is accomplished by eliminating any contributions to emittance growth from non-axisymmetric modes. These modes occur due to coupling slots cut into the accelerating cells and because of slug tuners and sample probes being placed at the outer radius of the accelerating cells. In addition, our design allows optimal placement of the emittance compensation solenoid over a short BNL/SLAC/UCLA-style gun[10]. We achieve this goal by complete preservation of axial symmetry and the elimination of any radial protrusions on the gun body. The microwave feed is brought in through a waveguide-to-coaxial transition and is delivered to the accelerating cells through a coaxial line at the rear of the gun. An axisymmetric tuning mechanism is designed into the structure for both accelerating cells.
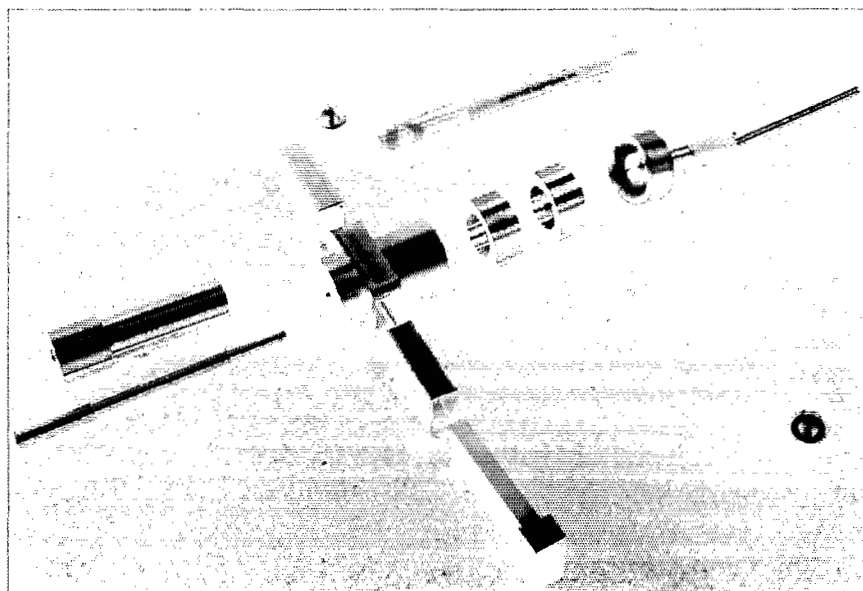

Figure 13. Low-power model parts for the axisymmetric gun.

Most of these features can be seen in the Figure 13 photograph which is reproduced as a negative in order to give better contrast with the dark background. This is an exploded view of the low-power model parts for this X-band gun. A ball point pen at the top center of the photo provides an indication of the scale involved. The two rings below the pen are the accelerating cavities, and the object to the right of the cavities is the end-cell tuning mechanism. The waveguide input arm can be seen to the immediate left of the pen with a sliding short for low-power model testing located opposite the input waveguide on the lower side of the cold model. The center conductor of the coaxial feed can be seen at the lower left.

The present design is in X-band at 11.4 GHz, but the overall concept can be scaled to any frequency. Beam dynamics analyses of the gun using PARMELA[23] have shown excellent performance characteristics over a range of bunch charges. The calculations have demonstrated a pronounced advantage in being able to place the emittance compensation solenoid over the accelerating structure.

Unlike the previous guns, this design is not intended to operate at CW or very high duty factor. Rather it is intended for very high-performance, high-peak-current, low-duty-factor applications such as the LCLS and Compton backscatter sources. The beam dynamics performance of this gun is summarized in Table 2 of the next section together with all the other injectors described above.

7. SUMMARY

We have described five different AES photocathode electron injector and a high-current SRF cryomodule project that are possible drivers for next generation x-ray sources. Each of these guns has a distinct niche in the broad realm of advanced radiation sources. To be accepted, they must deliver the beam performance required by the specific applications. Table 2 summarizes the simulation results for each injector and illustrates how they meet the application requirements that were defined above in Table 1. We have included the thermally modified conventional S-band RF gun in this table although the results were not specifically described. In this case we are repeating the specifications which we believe can be achieved in this gun although the emittance is particularly difficult.

Table 2: Simulated beam performance parameters for the guns under development

Parameter	CW DC Gun SRF	CW NC RF Gun	CW SRF NC Cathode	SRF Gun SC Cathode	Axisymme -tric Gun	Modified RF Gun	Units
Charge	0.147	3.0	1.34	0.01	1.0	1.0	nC
Beam Radius	0.98		1.2	7.3	0.34		mm rms
Transverse Emittance	1.2	6	4.2	0.748	0.764	< 1	microns rms
Bunch length	6.3		9.2	1.4	1.9		psec rms
Longitudinal Emittance	44	200	24.4	1.1	116	10	keV-psec rms
Energy	7.7	2.54	3.43	2.1	8.7	~ 5	MeV
Application	ERL	ERL	ERL	R&D	SASE FEL CBS	SASE FEL CBS	

The CW normal conducting gun and the SRF gun with a normal conducting cathode were not simulated at the lower bunch charge levels of an ERL light source. These two injectors were studied with higher power applications in mind. However, one can extrapolate from their high charge performance and see that they will readily meet the requirements of an x-ray source based on an energy recovery linac. This is especially true of the SRF gun with normal conducting cathode. The axisymmetric gun is a very attractive option for LCLS type sources and for Compton backscatter x-ray generators, while the fall back approach is a thermally-modified conventional S-band RF gun. The niobium cathode SRF gun is somewhat out of place and is really focused on R&D applications rather than the x-ray sources we have targeted here. However it was included for completeness. In conclusion, each of these guns is intended to overcome some limitation of existing photocathode injectors and open up new applications with their improved performance.

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